Microbial activity affected by lime in a long-term no-till soil

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Abstract

Under conventional farming practices, lime is usually applied on the soil surface and then incorporated into the soil to correct soil acidity. In no-till (NT) systems, where lime is surface applied or only incorporated into the soil to very shallow depth, lime will likely not move to where it is required within reasonable time. Consequently, lime may have to be incorporated into the soil by mechanical means. The objective of this laboratory study was to characterize the effect of lime, incorporated to different depths, on chemical and biological soil properties in a long-term NT soil. Soil samples taken from the 0–5, 0–10, and 0–20 cm depths were analyzed in incubation studies for soil pH, nitrate, CO_2 respiration, and microbial biomass-C (MBC). Lime ($CaCO_3$) was applied at rates equivalent to 0, 4.4, 8.8, and 17.6 Mg ha^{-1}. Application of lime to both 0–10 and 0–20 cm depths increased soil pH from about 4.9 by 1, 1.7, and 2.8 units for the low, medium, and high liming rates, respectively. Soil nitrate increased over time and in proportion to liming rate, suggesting that conditions were favorable for N-mineralization and nitrification. Greater respiration rates and greater MBC found in lime-treated than in non-limed soils were attributed to higher soil pH. Faster turnover rates and increased mineralization of organic matter were found in lime-treated than in non-limed soils. These studies show that below-surface lime placement is effective for correcting soil acidity under NT and that microbial activity and nitrification can be enhanced.

1. Introduction

In the non-irrigated region of the U.S. Pacific Northwest, decrease in soil pH is caused by acid-forming fertilizers and excessive leaching of bases (Mahler and Harder, 1984). Under no-till (NT) cropping systems, enhanced acidification can occur by repeated deep-banding of fertilizer and from the lack of soil mixing (Blevins et al., 1983). To correct soil acidification in NT soils, lime amendments have been typically applied to the soil surface without

incorporation (Mahler and Harder, 1984). However, agricultural liming materials are relatively insoluble, and lime effects may be restricted to the top few centimeters of soil surface for many years (Shainberg et al., 1989; Edmeades and Ridley, 2003). Mechanical incorporation of lime into the root zone may be necessary. No-till drills disturb the soil to at least 5 cm depth, some drills disturb the soil to 10 cm depth. If lime can be applied with such no-till drill operations, the lime can be incorporated to 5 or even 10 cm depths.

However, the chemical and biological effects of seed-placed lime in long-term NT soils are not completely known. Such effects are likely to differ from typical lime applications made under conventionally tilled soils. Indeed NT soils, particularly in the top few centimeters of surface soil, differ in their physical and biochemical properties as compared with conventionally tilled soils. Such difference can lead to changes in C dynamics (Doran et al., 1998; Curtin et al., 2000), and to different soil-environmental conditions that affect microorganisms (Alvarez et al., 1995; Bailey et al., 2002).

Agricultural liming materials, such as $CaCO_3$, increase soil pH and thereby affect the activity and composition of microbial populations (Tate, 2000). Microbial and chemical responses to lime vary with soil type and management. In acid soils, liming can create better environmental conditions for the development of acid-intolerant microorganisms resulting in increased microbial biomass and soil respiration (Neale et al., 1997). Shah et al. (1990) showed a 20-fold increase in bacterial numbers after the application of 7.5 Mg ha^{-1} of ground limestone to an acidic podzolic soil.

In soils with a weakly acidic character, increased pH caused by lime can enhance soil respiration as well as N-mineralization by the release of labile organic matter in the form of dissolved organic compounds (Curtin et al., 1998). Increased bioavailability is a desta-bilization process where soil organic matter becomes less resistant to degradation and more accessible to microorganisms and soil enzymes (Sollins et al., 1993). The increase in pH enhances the deprotonation of organic substances and, as a result, the bonding between organic compounds and soil particles decreases, making organic substances more available for microbial consumption (Curtin et al., 1998).

Microbiological effects of lime have been well documented for acidic soils under different management systems including some NT soils (e.g., Shah et al., 1990; Curtin et al., 1998; Bezdicek et al., 2003). In the Palouse Region of Washington State, banding N, P, and S fertilizers in NT soils has increased soil acidity in the seed zone. Few studies have addressed the chemical and biological effects of incorporating liming materials into the acidified seed zone under NT. The aim of this study was to characterize the effect of lime applications to different depths on soil pH, nitrate, soil respiration, and MBC of a soil managed under NT for 29 years.

2. Materials and methods

2.1. Soil sampling and processing

The soil was collected from a wheat (*Triticum aestivum* L.) field managed for 29 years under NT located 20 km north of Pullman, WA (46°55′N/ 117°11′W). The field was on a mid-slope landscape position with a 2–3% slope and northeastern aspect under a lentil (*Lens culinaris*)/winter wheat/spring wheat rotation. Annual fertilization was 120 kg N/ha for winter wheat and 80 kg N/ha for spring wheat applied as anhydrous ammonia in a deep band 5 cm below the seed. The soil is mapped as a Palouse silt loam (Donaldson, 1980).

We collected 12 soil samples randomly from a 15 m × l5 m plot from 0–5, 0–10, and 0–20 cm depth layers, respectively, in April 2002. Soil was sampled with a probe of 12 cm diameter and 5 cm depth. Previous work demonstrated that under NT the 5–10 cm zone was most vulnerable to acidification because fertilizers were typically applied in this zone (Bezdicek et al., 2003). If lime were applied to a NT soil, lime could be mixed to a depth of about 5 cm with a low-disturbance NT drill. For other NT drills, such as hoe-type openers and heavy double-disk openers, soil could be disturbed to a depth of about 10 cm. Our first two sampling intervals therefore represented realistic depths to which lime could be applied in a NT soil. The third sampling layer (0–20 cm) represented a situation where a farmer plowed the soil after several years of no-till to remedy soil acidification.

Soil samples were pooled by depth interval, passed through a 2 mm sieve, and mixed thoroughly. Five grams of each soil sample were mixed with 30 mL of a 0.1 M $MgSO_4$ solution and shaken for 1 h. The soil

solution was then filtered and the concentration of NO_3-N was measured using an ion-selective electrode (Dahnke and Johnson, 1990). Organic C and total N were measured by dry combustion with a LECO CHN Analyzer (Leco Corporation, St Joseph, MI). Water content at $-33\ J\ kg^{-1}$ was determined with a pressure plate extractor (Soilmoisture Equipment Corp., Goleta, CA). All measurements were made in triplicate.

Prior to incubations, sieved soil samples were stored in high-density polyethylene (HDPE) boxes and kept in the laboratory at $22 \pm 2\ ^{\circ}C$ for 10 days. The boxes were opened daily to release CO_2 flushes due to sieving and mixing.

2.2. Soil incubation

Liming treatments consisted of fine-powder $CaCO_3$ (passed through a 125 μm sieve) applied at rates of 1.96, 3.93, and 7.86 g $CaCO_3$ per kg soil, equivalent to 4.4, 8.8, and 17.6 Mg $CaCO_3$ ha^{-1}. Lime was applied on a mass basis, i.e., all three depths (0–5, 0–10, and 0–20 cm) received the same amount of lime per treatment. This did not mimic field application of lime, but ensured that pH and microbial response of soils to lime treatment could be compared. A no-lime treatment served as control. Lime was thoroughly mixed with the soil. Soil samples used for inorganic N, pH, and soil respiration-biomass characterization were amended with a KNO_3 solution to adjust all samples to 75 mg NO_3^--N kg^{-1} soil. The quantity of KNO_3 required was added to the amount of water needed to raise the actual soil water content to a water potential of $-33\ J\ kg^{-1}$. The amount of NO_3^- added adjusted the NO_3^- content of the samples to a level equivalent to field measured NO_3^- in spring (Bezdicek et al., 2003). Standardization of NO_3^- level allowed us to investigate the effect of liming on NO_3^- and NH_4^+ levels in soil.

Lime-treated samples plus an untreated control were used for pH, N, soil respiration, and microbial biomass experiments described below. All treatments were replicated four to six times and incubated in the dark for up to 149 days at $22 \pm 2\ ^{\circ}C$.

2.3. Soil pH, nitrate and ammonium

To determine pH, NO_3^- and NH_4^+, lime was applied to 10 g (dry basis) soil samples and placed in 60 mL HDPE bottles. Bottles were loosely capped

allowing air exchange. Water loss from soil sub-samples was minimized by storing the bottles in 29 L sealed HDPE boxes (37 cm × 52 cm × l5 cm) containing 100 mL beakers filled with water. Boxes were periodically opened to allow air exchange. Soil pH was determined in triplicate in a 1:1 (w:v) soil-to-water suspension at 1, 7, 14, and 56 days of incubation. Soil NO_3^--N and NH_4^+-N were measured at 1, 14, 28, and 56 days of incubation, by colorimetry using an Alpkem continuous flow analyzer (Alpkem Corporation, Clackamas, OR). At each sampling time period, four subsamples per treatment were taken.

2.4. Soil respiration and microbial biomass-C

Lime treatments were applied to soil samples of 250 g (dry basis). Samples were initially kept in open 1.9 L HDPE containers for 12 h to allow the release of the CO_2 evolved due to the initial $CaCO_3$ reaction with the soil. To minimize soil water evaporation during the 12 h period, laboratory air was humidified. Then, subsamples of 5 g (dry basis) were removed and placed in 40 mL tubes and sealed with a cap containing a Teflon septum. Soil respiration was measured from CO_2 evolved at 1, 2, 4, 6, 8, 14, 21, 28, 42, 57, 77, 98, 124, and 149 days of incubation. Six tubes per treatment-depth were randomly chosen and CO_2 was quantified with a gas chromatograph equipped with a thermal conductivity detector (Shimadzu GC-17, Shimadzu Corp., Kyoto, Japan). After determining microbial respiration, all tubes were flushed with water-saturated air and recapped to prevent soil drying.

For microbial biomass-C (MBC) determination, we added 0.125 mL of 24 g L^{-1} glucose solution to 250 g soil (dry basis), replicated four times. Tubes were kept open for 2 h to allow air exchange and then capped. The MBC was measured with the substrate-induced respiration method (Anderson and Domsch, 1978) at 1, 14, 28, 56, and 149 days of incubation. After MBC determination, the samples were discarded. Microbial biomass-C was calculated from (Anderson and Domsch, 1978):

$$MBC = 40.04x + 0.37 \tag{1}$$

where MBC has units of mg/100 g soil and x is the maximum initial rate of CO_2-C respiration (mL CO_2-C/100 g soil h) from 0 to 3 h of incubation.

Microbial biomass-C was also estimated by the chloroform fumigation method (Horwath and Paul,

1994). We used 350 g of soil for each treatment and incubated the treatments using 1.9 L HDPE containers. Tygon tubes were inserted in the caps of the containers to allow air exchange. Soil water was maintained by placing a beaker filled with deionized water on top of the soil. Five subsamples were obtained from each treatment at 14, 28, and 56 days of incubation. For each treatment, three subsamples were fumigated and two were used as non-fumigated controls. Microbial biomass-C was then calculated as:

$$\text{MBC} = \frac{C_f - 0.18 C_c}{k_c} \qquad (2)$$

where C_f (mg CO_2-C/100 g soil) is the CO_2-C produced from a chloroform fumigated sample, C_c is the CO_2-C produced from a non-fumigated (control) sample (mg CO_2-C/100 g soil) and k_c is the fraction of MBC that is mineralized to CO_2-C. The value of k_c was considered a constant equal to 0.41 (Horwath and Paul, 1994). Following the recommendations of Smith et al. (1995), we used 18% of the measured value of C_c. The chloroform fumigation method was used to check the substrate-induced respiration method, and to verify that the addition of glucose did not lead to errors in MBC estimations.

2.5. Data analysis

Nitrogen mineralization and MBC were analyzed using a complete randomized design with factorial structure. If assumptions of normality and homogeneity of variances were violated, we performed a non-parametric test (Zar, 1999). We report significant differences based on the non-parametric analysis, but means and standard errors of the raw data were kept.

Correlation analysis between MBC methods was performed by controlling the effects of depth, time, and lime. Soil respiration was analyzed for each liming treatment with a first-order model describing the cumulative amount of CO_2-C produced as a function of time. This model has also been used to describe N-mineralization (Jones, 1984):

$$C_t = C_e + C_0(1 - e^{-kt}) \qquad (3)$$

where C_t (mg CO_2-C kg^{-1} soil) is the cumulative amount of CO_2-C mineralized at time t, and C_e the easily mineralizable C pool (mg CO_2-C kg^{-1} soil), which is rapidly consumed during the first few days of incubation. In our study, this parameter might also have accounted for the potential flushes of CO_2 due to initial reaction of soil with lime. The parameter C_0 is the potentially mineralizable C (mg CO_2-C kg^{-1} soil), and k (day^{-1}) corresponds to the fraction of C mineralized per day (Ellert and Bettany, 1988; Curtin et al., 1998). The model was fitted to the data using a non-linear regression analysis with the NLIN procedure of SAS 8.0 (SAS Institute, Cary, NC). Fitted parameters C_e, C_0, and k were statistically compared among liming treatments and sampling depths by using the 95% confidence intervals obtained from the procedure fitting. Analysis of variance and correlation were carried out with the GLM and CORR procedures of SAS.

3. Results and discussion

3.1. Soil properties

Characteristics of soil prior to lime treatments are shown in Table 1. A decrease in NO_3^--N, pH, and

Table 1
Selected soil properties prior to experimental treatment

Sampling depth (cm)	NO_3^--N (mg kg^{-1})	Water content at -33 J kg^{-1} (g g^{-1})	Soil pH (1:1 water)	Organic C % by weight	Total N % by weight	C/N ratio[a] % by weight
0–5	27.4 ± 0.9	0.36 ± 0.01	5.4 ± 0.2	3.36 ± 0.01	0.25 ± 0.01	13.7
0–10	19.5 ± 0.5	0.31 ± 0.01	4.8 ± 0.1	2.81 ± 0.03	0.20 ± 0.01	14.1
0–20	13.4 ± 0.4	0.29 ± 0.01	4.9 ± 0.1	2.52 ± 0.02	0.17 ± 0.01	14.5
5–10[b]	NA[c]	0.29 ± 0.01	4.9 ± 0.1	2.47 ± 0.02	0.17 ± 0.01	14.1
10–20[b]	NA[c]	0.28 ± 0.01	5.1 ± 0.1	2.31 ± 0.02	0.16 ± 0.01	14.9

Values are mean and standard deviation ($n = 3$).
[a] Ratio of the means.
[b] Depths sampled to provide data on pH stratification.
[c] Not available.

organic matter was observed when the soil was mixed over 0–10 and 0–20 cm depths compared to the 0–5 cm depth. The zone of greatest acidification was at 5–10 cm depth, coinciding with a typical depth of fertilizer placement.

3.2. Soil pH

One day after incorporation of lime, soil pH increased by 1.0, 1.5, and 1.9 units for liming rates of 4.4, 8.8, and 17.6 Mg $CaCO_3$ ha^{-1}, respectively, when averaged across soil depths (Fig. 1). From 14 to 56 days of incubation, further increases in soil pH were most obvious at the 17.6 Mg $CaCO_3$ ha^{-1} rate. At 56 days, lime at 17.6 Mg $CaCO_3$ ha^{-1} increased soil pH by 2.8 units as compared to the control. At 56 days of incubation, differences in pH between sampling depths were within 0.1 pH units for each liming rate (Fig. 1). This indicates that soil mixing to 10 or 20 cm depths provided a similar pH environment for microbial activity in a relatively short period of time. For all liming rates and depths, soil pH increased from strongly acidic to near neutral conditions. Bezdicek et al. (2003) reported seasonal increases in soil pH of 0.1–0.8 units, 18 months after 2.6 Mg ha^{-1} pelletized lime (>91% $CaCO_3$) was broadcast and incorporated into Palouse soils of Washington and Idaho. Their observed increases were similar to those reported in our study for the lowest liming rate.

3.3. Soil nitrate and ammonium

The statistical analysis of NO_3^--N showed significant interactions with depth × time × lime, time - × lime, and depth × time (Table 2). The effect of lime was not consistent across all measurement periods and depths. However, since the main effects of depth, time, and lime were highly significant (values of F for depth, time, and lime were numerically much higher than those for interactions), we will discuss results of the main effects only. The 0–5 and 0–10 cm sampling depths showed significantly higher ($P < 0.01$) NO_3^--N than at the 0–20 cm depth (Table 1). The 0–10 and 0–20 cm samples had less organic matter per unit of soil mass than the 0–5 cm samples, and likely had reduced soil microbial activity.

The significant ($P < 0.01$) effect of time suggests a consistent increase of NO_3^--N from nitrification of
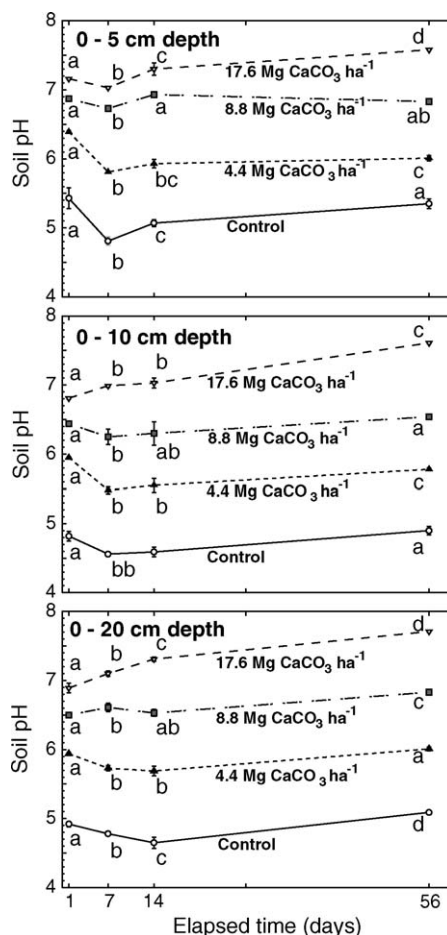

Fig. 1. Variation of soil pH with time for different liming rates and sampling depths. Error bars indicate ±one standard deviation of the mean. Letters indicate least significant differences ($P < 0.01$) for time at each level of lime and should be compared in the horizontal direction.

NH_4^+ (Fig. 2). The effect of liming on NO_3^- production with time was greater in the 0–5 and 0–10 cm sampling depths. At 56 days, NO_3^--N levels increased consistently with the highest liming rate in all sampling depths.

Values of pH > 5.5 are associated with optimal pH levels for the development and growth of nitrifiers (Myrold, 1998; Tate, 2000). In our study, liming rates > 4.4 Mg $CaCO_3$ ha^{-1} increased soil pH to values >5.5 (Fig. 1), thereby creating adequate environmental conditions for nitrification. However, it is difficult to attribute increased NO_3^--N only to

Table 2
Analysis of variance for NO_3^--N, NH_4^+-N, and microbial biomass-C by substrate-induced respiration for the factors: liming rate (lime), sampling time (time), depth of application (depth), and their interactions

Parameter	Depth	Time	Depth × time	Lime	Depth × lime	Time × lime	Depth × time × lime
NO_3^--N							
Significance	***	***	**	***	NS	***	*
F	219.1	129.7	4.2	18.4	0.6	4.5	2.0
d.f.	2	3	6	3	6	9	18
NH_4^+-N							
Significance	***	***	**	*	NS	NS	NS
F	22.5	25.9	3.9	2.9	0.7	1.1	0.9
d.f.	2	3	6	3	6	9	18
Microbial biomass-C							
Significance	***	***	***	***	NS	NS	*
F	216.7	152.7	28.5	55.4	0.4	1.0	2.0
d.f.	2	3	6	3	6	9	18

NS: not significant, d.f.: degrees of freedom.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

adequate levels of pH. We hypothesize that a fraction of the more stable pool of organic matter was also available for mineralization after its reaction with $CaCO_3$. Solubilization of organic matter in acidic soils after liming has been reported by others (e.g., Curtin et al., 1998; Andersson and Nilsson, 2001).

Levels of NH_4^+ were significantly different with time, depth, depth × time, and lime (Table 2). In general, values of NH_4^+-N were lower than 2.5 mg kg^{-1} soil, with a decrease after liming application on the order of 0.5 mg kg^{-1} (data not shown). Small concentrations as well as the temporal variation can be explained by the rapid oxidation of NH_4^+ to NO_3^-.

3.4. Soil respiration

During the first day of incubation, and at all sampling depths, CO_2-C respiration increased with liming rate by about one order of magnitude compared to the control (Fig. 3). Cumulative CO_2-C released was well described by the first-order model (Fig. 3). Potentially mineralizable carbon, C_0, was significantly greater in the 0–5 cm depth than in the 0–10 and 0–20 cm depths (Table 3). Liming significantly increased C_0, but its effect was more noticeable at the 8.8 and 17.6 Mg $CaCO_3$ ha^{-1} rates. The readily mineralizable

fraction of organic matter, C_e, increased significantly with lime at all depths. Values of C_e were not consistently different between sampling depths at equal liming rates. We hypothesize that the C_e parameter accounted for both the initial abiotic flush of CO_2 due to the reaction of $CaCO_3$ with soil, as well as for a rapid biological CO_2 flush.

The first-order rate constant, k, was not affected appreciably by mixing soil over depth (Table 3). In most cases, application of lime significantly increased k, but the effect of increased liming rate on k was not consistent in all depths. We observed smaller microbial turnover times with increased lime (Fig. 3), which suggests increased availability of readily mineralizable organic matter to soil microorganisms. Decreases in turnover times from 100 to 46 days were reported by Curtin et al. (1998) for soils limed with $Ca(OH)_2$.

3.5. Microbial biomass-C

The statistical analysis of MBC with substrate-induced respiration showed significant interactions with all combinations of the factors depth, time and lime (Table 2). Hence, we performed the ANOVA, partitioning the effect of lime at each level of time and depth. Microbial biomass-C increased with lime at
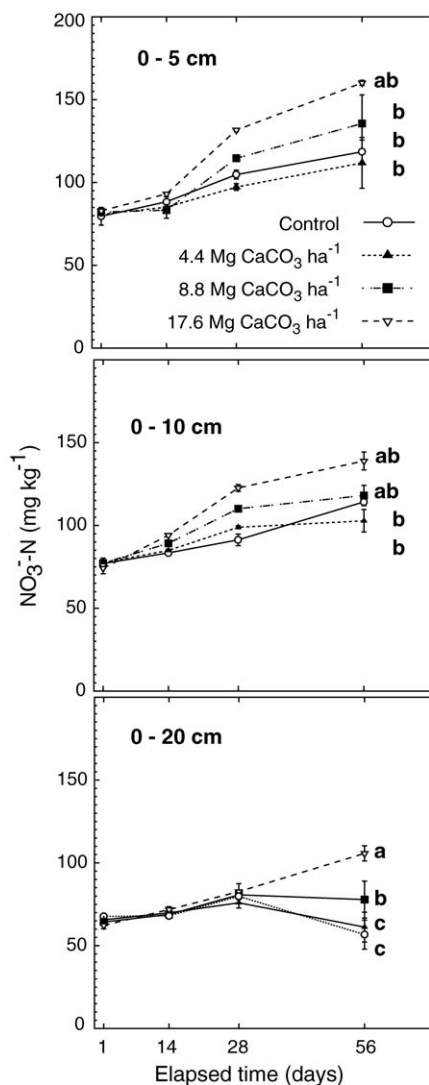
Fig. 2. Soil NO_3-N accumulation with time for different sampling depths and lime application rates. Error bars indicate ±one standard error of the mean ($n = 4$). Letters indicate least significant differences ($P < 0.01$) for liming rate at 56 days.
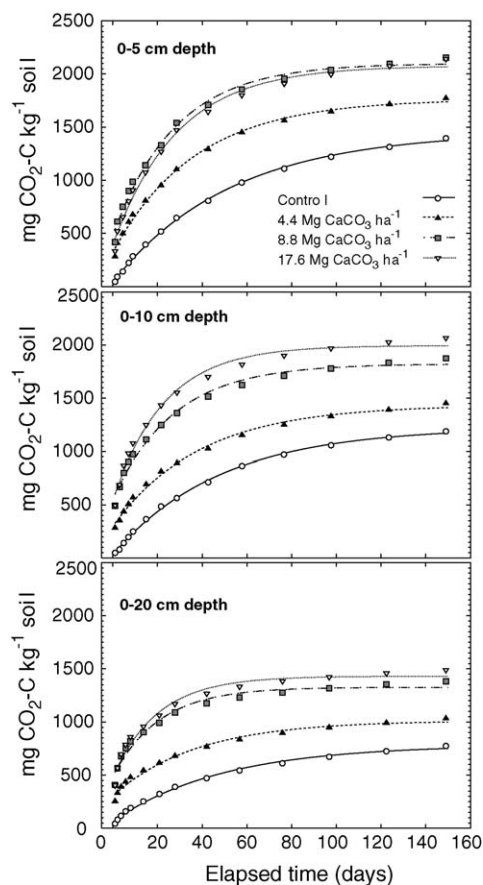

Fig. 3. Cumulative CO_2-C released as affected by liming and sampling depth. Lines correspond to the fitted first-order kinetics model with parameters values in Table 3.

almost all sampling times and decreased with sample depth. Increases in MBC due to liming have been reported extensively in the literatures (Ivarson, 1977; Neale et al., 1997; Bezdicek et al., 2003). Differences in MBC were most significant when comparing the control with any of the three liming rates. Increasing rate lime from 4.4 to 17.6 Mg $CaCO_3$ ha^{-1} did not consistently increase MBC for all depths (data not

shown). Determination of MBC by substrate-induced respiration requires the application of glucose and mechanical re-mixing of soil. As a result, MBC can be overestimated if unreacted $CaCO_3$ particles were dissolved and released as CO_2 during the assay. Therefore, we performed a parallel study of MBC determined by chloroform fumigation to verify the results. The fumigation method showed more pronounced differences between the control and the three liming rates. Averaged across times and depths, MBC with fumigation was 3.3, 4.4, and 7.2 times greater than the control at rates of 4.4, 8.8, and 17.6 Mg $CaCO_3$ ha^{-1}, respectively. From means of the three depths at 14, 28, and 56 days, MBC methods were significantly correlated ($P < 0.0001$).

Table 3
Potentially mineralizable C (C_0) easily mineralizable C pool (C_e) and mineralization rate (k) for cumulative CO_2-C release, and coefficient of determination (R^2) obtained by non-linear parameter estimation

Liming rate (Mg $CaCO_3$ ha^{-1})	C_0 (mg CO_2-C kg^{-1})	C_e (mg CO_2-C kg^{-1})	k (day^{-1})	$1/k$ (days)	R^2
0–5 cm					
Control	1418 ± 18 a[a]	41 ± 9 a	0.019 ± 0.001 a	53	0.999
4.4	1442 ± 27 a	321 ± 20 b	0.027 ± 0.002 b	37	0.997
8.8	1620 ± 42 b	481 ± 35 c	0.036 ± 0.003 b	28	0.993
17.6	1684 ± 43 b	393 ± 36 bc	0.035 ± 0.003 b	29	0.993
0–10 cm					
Control	1193 ± 15 a	31 ± 9 a	0.021 ± 0.001 a	48	0.999
4.4	1136 ± 26 a	299 ± 19 b	0.026 ± 0.002 ab	39	0.995
8.8	1269 ± 41 ab	554 ± 36 c	0.037 ± 0.004 bc	27	0.989
17.6	1457 ± 47 b	537 ± 43 bc	0.044 ± 0.004 c	23	0.989
0–20 cm					
Control	722 ± 19 a	64 ± 10 a	0.02 ± 0.002 a	49	0.995
4.4	708 ± 26 a	305 ± 18 b	0.027 ± 0.003 ab	38	0.987
8.8	838 ± 42 ab	489 ± 39 c	0.048 ± 0.007 bc	21	0.973
17.6	949 ± 45 b	481 ± 41 c	0.050 ± 0.007 c	20	0.976

Values are mean and standard error of fitted parameters.
[a] Letters indicate significant differences ($P < 0.05$) for the effect of lime.

4. Conclusions

This study showed that pH in NT soil responded rapidly to incorporation of lime. The highest liming rate of 17.6 Mg $CaCO_3$ ha^{-1} neutralized soil acidity and generated pH values greater than 7.5 at 56 days of incubation. Soil nitrate increased with time in proportion to liming rate, suggesting that conditions were favorable for N-mineralization and nitrification.

Initial CO_2 evolution was highest at 1 day and increased with liming rate. However, a shift occurred at 57 days, where non-limed soils had greater respiration than limed soils. Formation of readily decomposable organic matter from more reactive pools and better environmental conditions for microbial growth may have caused an initial respiratory response in limed soils. When this readily decomposable organic pool was consumed, less substrate was available for further decomposition. The effect of lime on potentially mineralizable carbon was proportional to liming rate and decreased with soil depth.

For all sampling depths, the readily mineralizable fraction of organic matter was 7.5–12.5 times greater in limed than in non-limed soil. This initial fast-release of CO_2-C after lime application was likely affected by two parallel processes: a non-biological flush of CO_2-C presumably caused by the reaction of

$CaCO_3$ with soil particles, and the biological respiratory flush caused by improved environmental conditions for microbial growth (i.e., more availability of organic substrates and increased pH). Microbial biomass also increased with liming rate, but slowly decreased with time. This pattern confirms that liming immediately improved and sustained favorable conditions for microbial growth and activity.

These results suggest that lime placed in the seed zone was effective in controlling soil acidity by increasing soil pH, and in increasing soil nitrate, respiration, and MBC. However, faster turnover rates of organic matter in limed soils, as well as increased C mineralization potentials, might be seen as detrimental from a C storage view point. This is of particular importance under NT soils, where C sequestration is seen as an additional benefit as compared with conventional-tilled soils.

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